MHD Simulation of Solar Wind Dynamic Pressure Changes

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Abstract

A sudden increase in the solar wind dynamic pressure compresses the magnetosphere and launches compressional waves into the magnetosphere. Using BATS-R-US, a global 3D MHD model developed by the University of Michigan, we will study the different responses of the magnetosphere to three different solar wind dynamic pressure changes. One case will involve a slow solar wind density step increase. The second case will involve a more rapid step increase. The third case will be a solar wind density pulse. The differences in the global responses of the magnetosphere for the three cases will be presented. In particular, we will look at the differences in the responses of the ionosphere for the step increase and the pulse. We will compare the results of the simulation to current theories of field-aligned current generation from dynamic pressure changes.

Dayside Response to a Pressure Pulse

Two sets of theories:

–FAC generated at or near the magnetopause. (Glassmeier and Heppner [1992], Kivelson and Southwood [1991], Sibeck [1990])

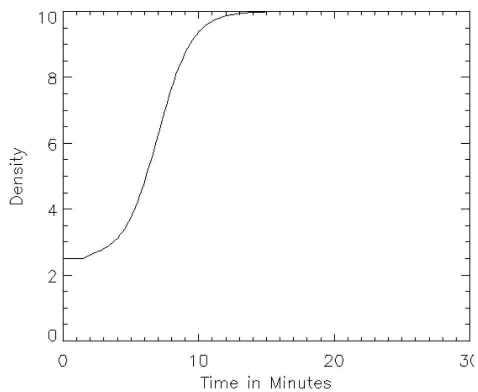
–Compressional waves excited at the magnetopause. These waves propagate into the magnetosphere where this mode could convert to an Alfvén wave. (Tamao [1964], Lysak and Lee [1992], Araki [1994])

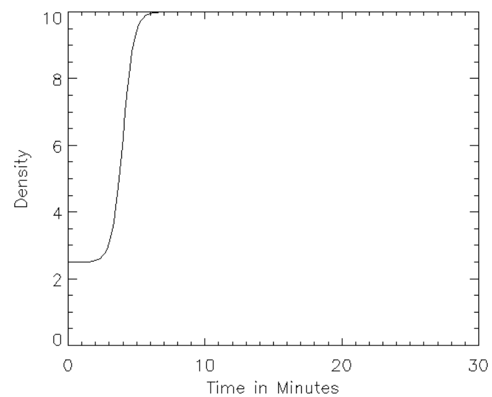
Simulation Information

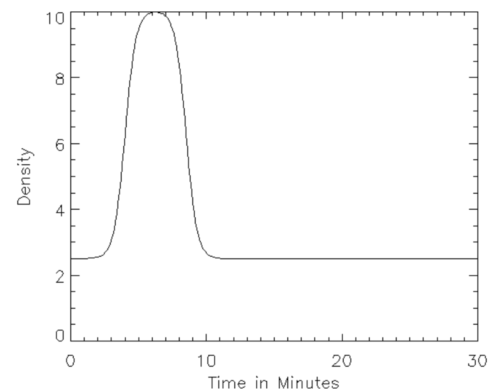
- BATS-R-US uses an adaptive grid that allows higher resolution in regions of interest. In this run, the smallest resolution was 0.25 R_E. After the initial setup, the grid was fixed. There were approximately 2 million cells.
- The solar wind velocity is 340 km/s and the IMF is 1 nT and northward.
- The ionosphere has a constant Pedersen conductivity with $\Sigma_P = 5$ mhos.
- Corotation is implemented in this run. This allows the breaking of the symmetry.
- The dipole tilt is set to zero.

Density Input

- Step Increase 1
- Step Increase 2
- Pulse

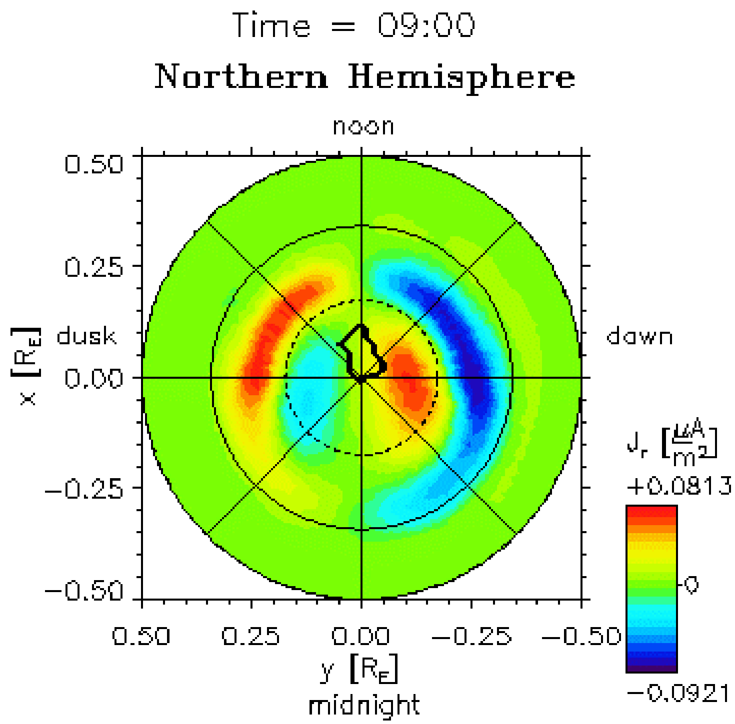


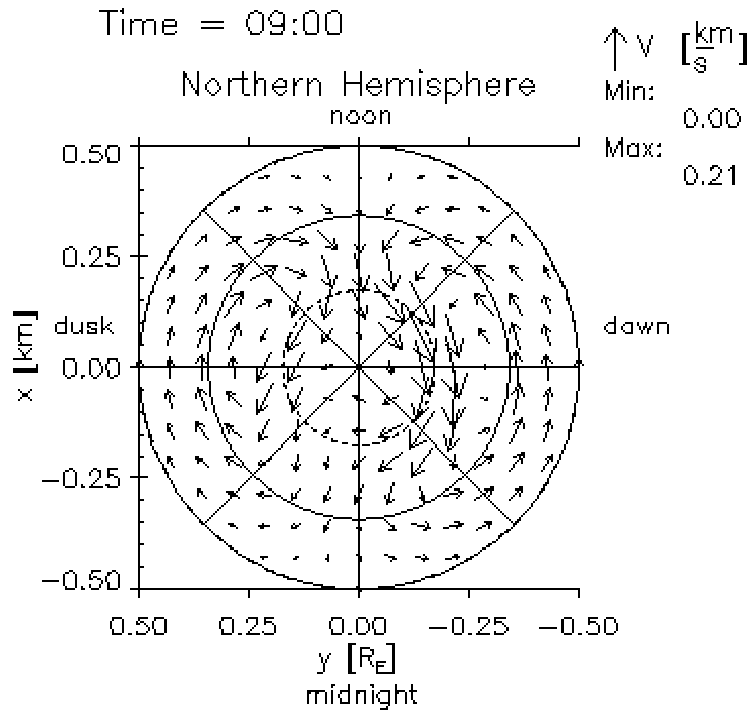




- For the first step increase the sharpest rise time is about 4 minutes from about 5 to 9 minutes.
- For the second step increase and the pulse, the rise time is about 2 minutes.

Initial Ionosphere

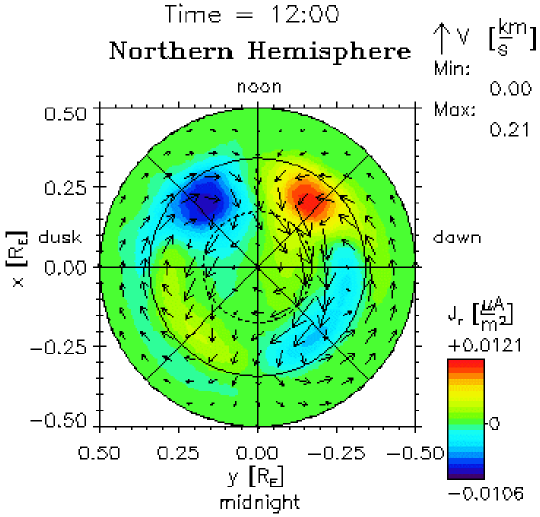




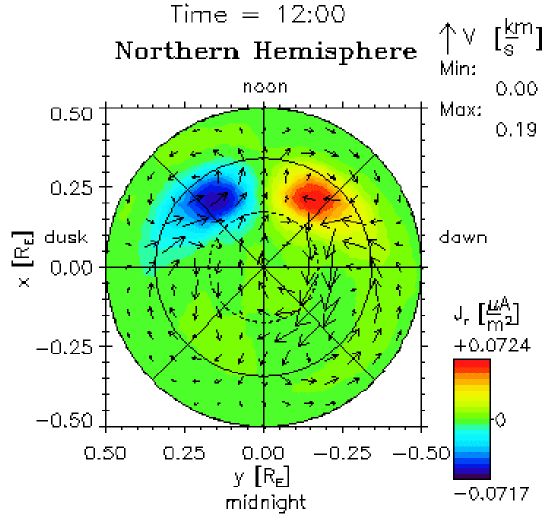
- The left plot shows the current density and the open/closed field line boundary. The right plot shows the velocity vectors.
- The initial ionosphere at 9 minutes is similar for all cases. The case shown here is for the slow step case.

Currents in the Ionosphere at t=12 min.

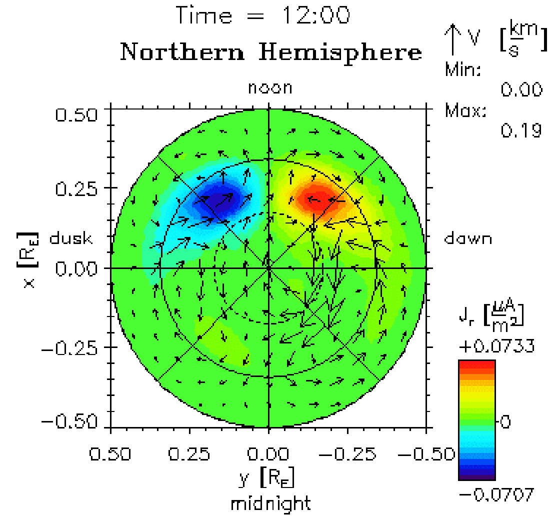
- Slow Step Increase



- Fast Step Increase

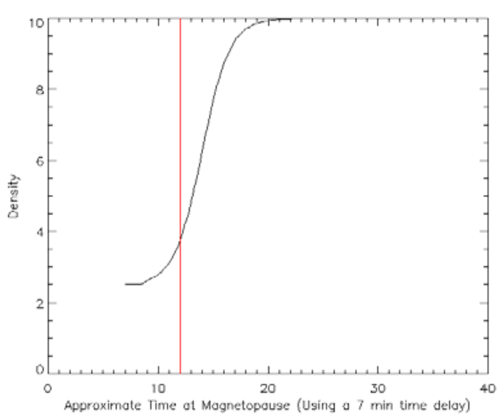


- Pulse

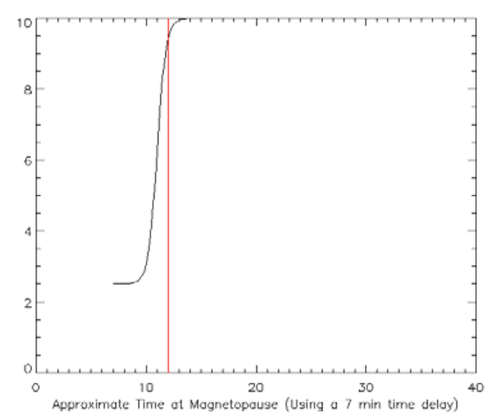


The current density is the difference between t=12 and t=9 minutes. The slow step increase is on a smaller scale than the other two cases. The velocity is the velocity at t=12 minutes.

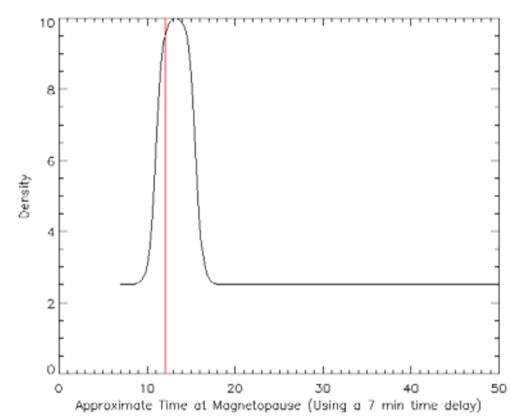
Step 1



Step 2

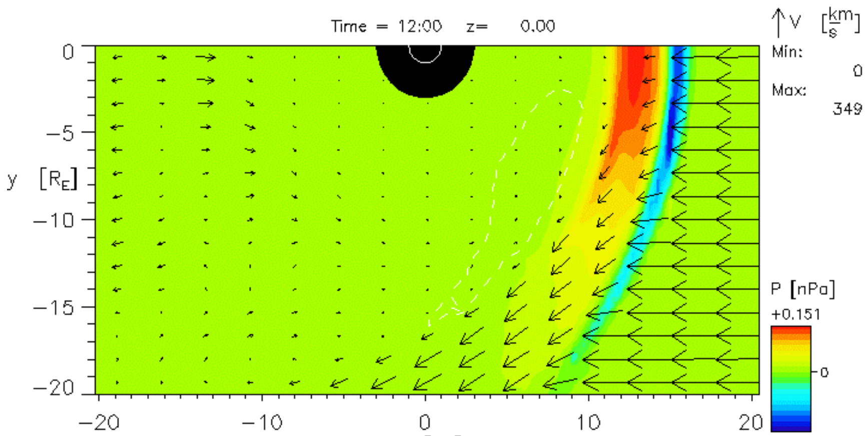


Pulse

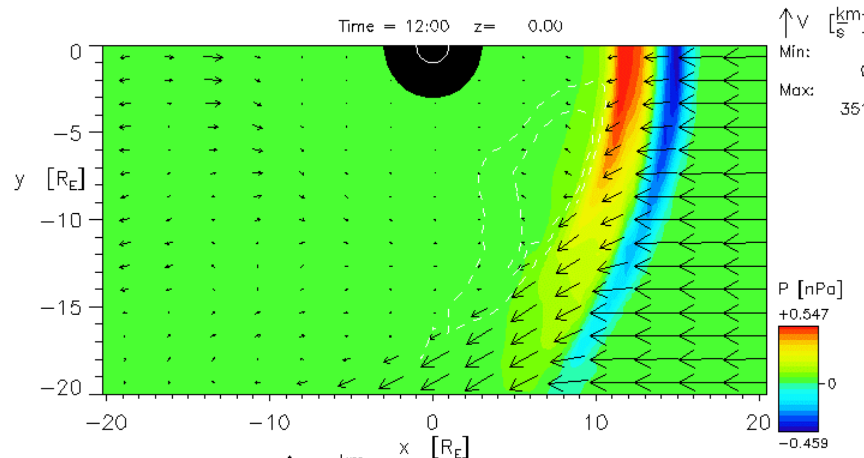


Velocity Profiles in Equatorial Plane

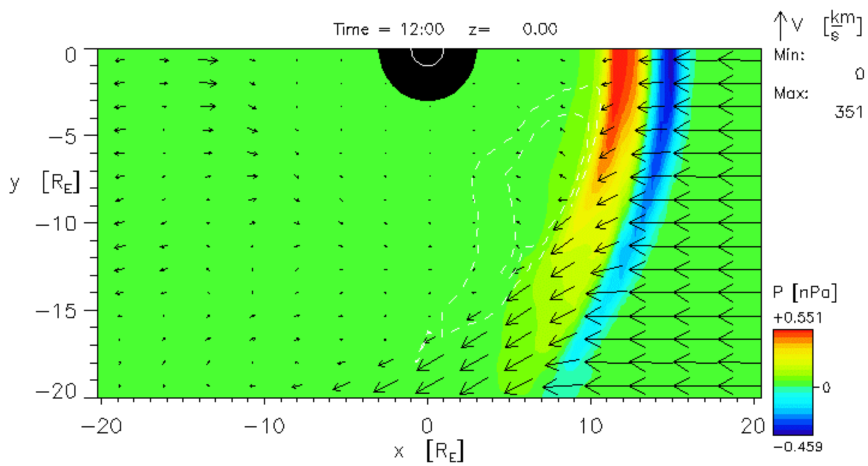
- Slow Step Increase



- Fast Step Increase



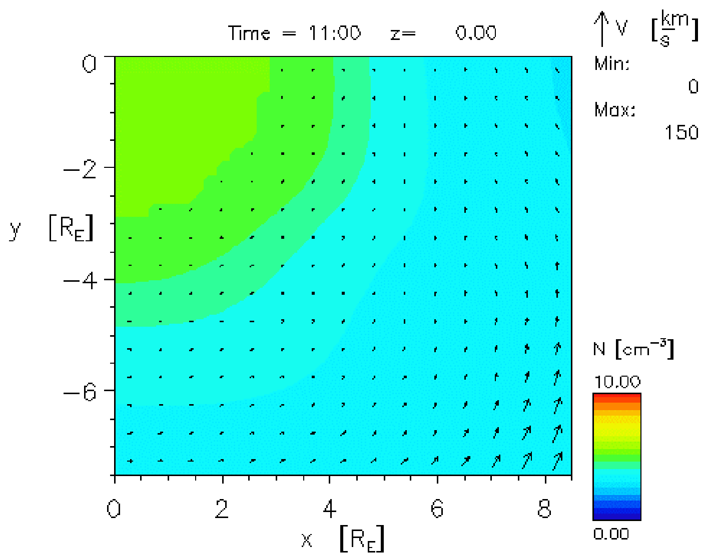
- Pulse



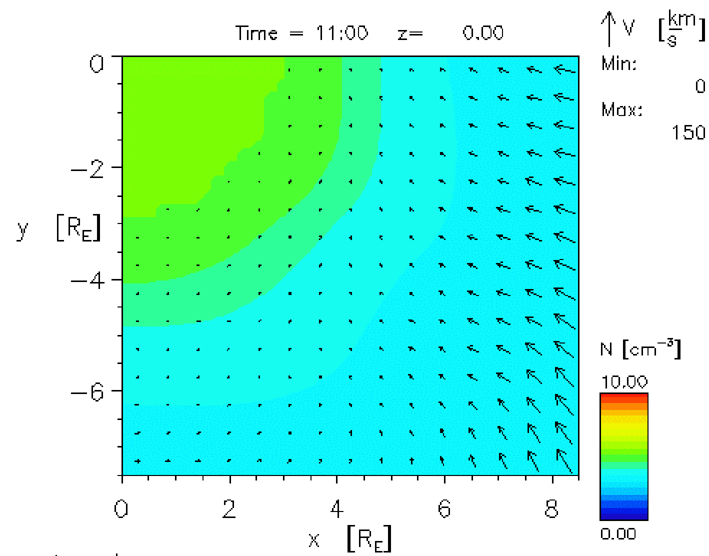
The pressure is the difference between t=12 and t=9 minutes. The velocity is the velocity at t=12 minutes. Contours show where the newly formed current in the ionosphere maps to in the equatorial plane. The contour level for the slow step case is smaller than the contour levels in the two steeper cases. Dotted lines are for positive currents in the ionosphere.

Velocity Profiles in Equatorial Plane

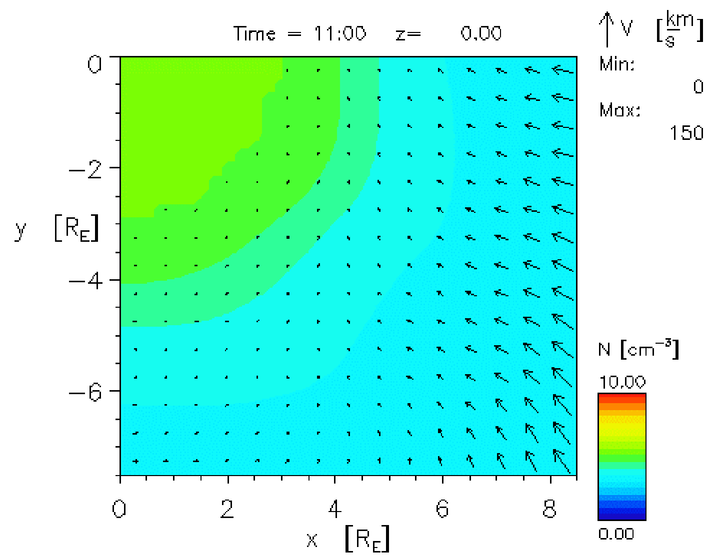
Slow Step Increase



Fast Step Increase



Pulse

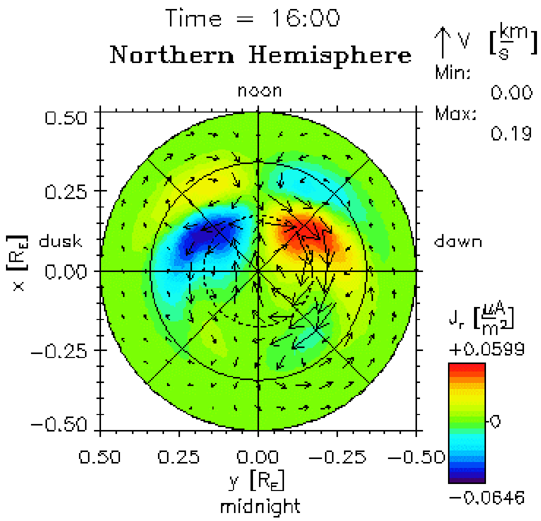


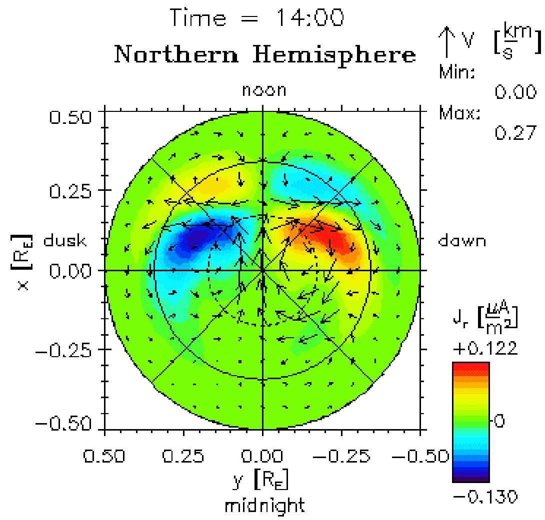
First Response

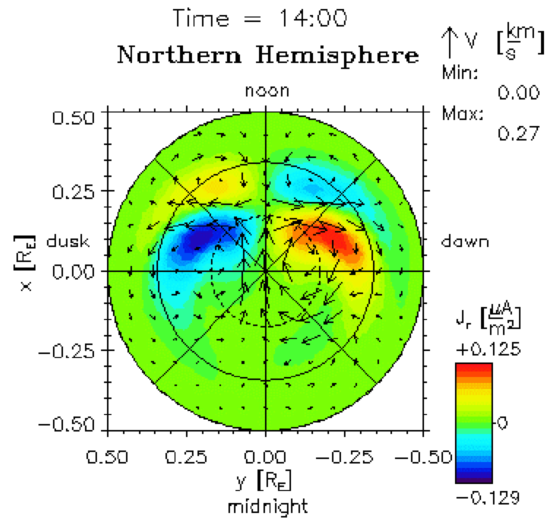
- All three cases have a first response that has current going out of the ionosphere on the dawn side and into the ionosphere on the dusk side.
- From about 11 to 13 minutes, the difference in current density in the ionosphere is 5-6 times larger for the steeper step and pulse cases than for the first step increase. The pattern and location for the current density are similar for both cases.
- The velocity patterns in the ionosphere at t=12 minutes are significantly different. A vortex forms in the two steeper cases. While for the first step case, the velocity pattern is similar to the velocity pattern before the density increase.
- In the magnetosphere, the newly-formed currents in the ionosphere map to similar regions in the equatorial plane. In this region, the velocity is significantly larger for the two steeper cases. There is a large velocity at the magnetopause directed toward the Earth.

Currents in the Ionosphere

- Slow Step Increase
- Fast Step Increase
- Pulse

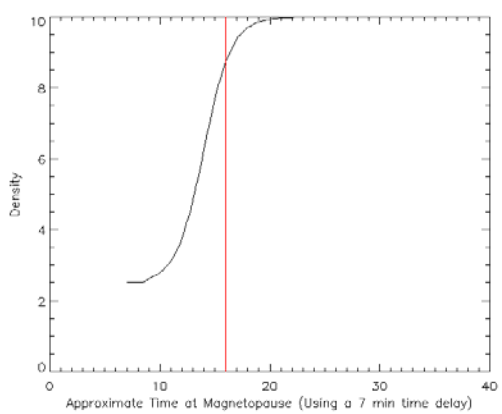




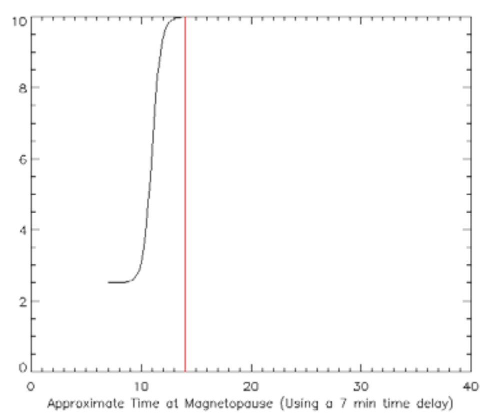


The current density is the difference plot from t=9 minutes. The velocity plot is not a difference plot but the actual velocity at that time.

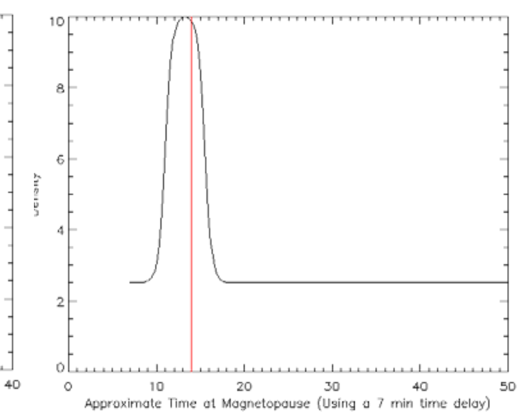
Step 1



Step 2

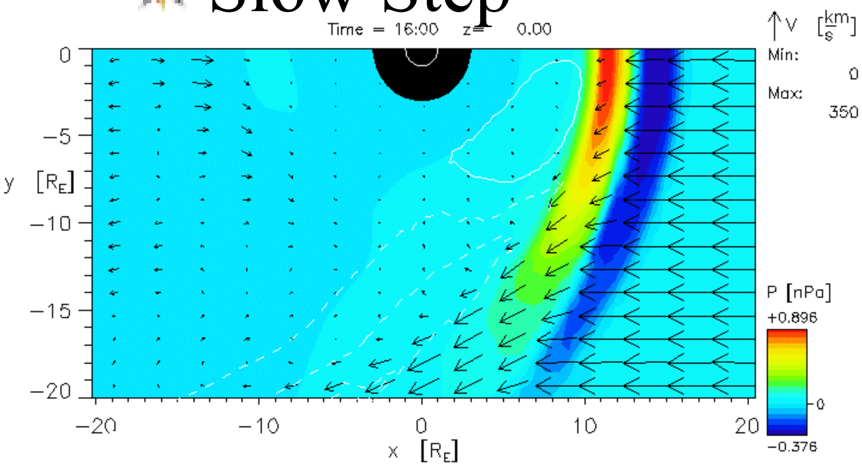


Pulse

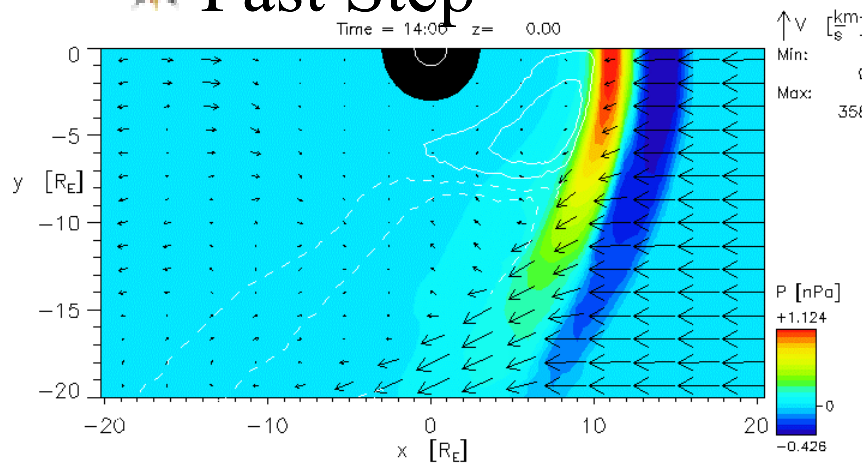


Velocity in the Equatorial Plane

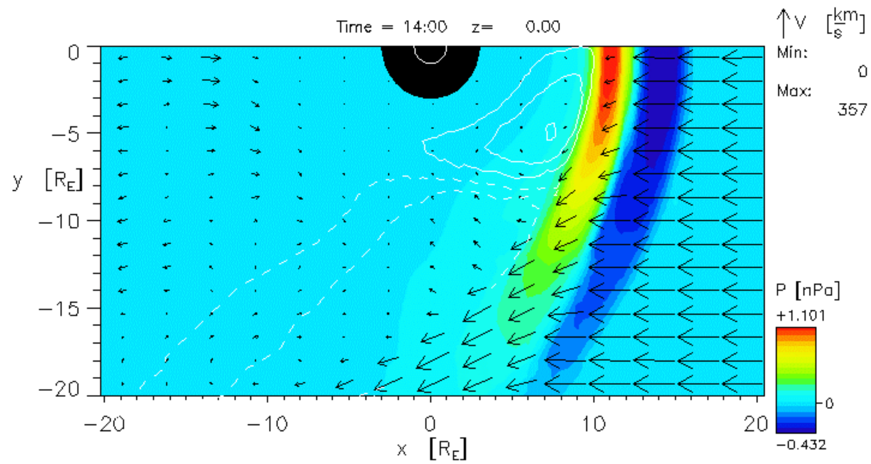
Slow Step



Fast Step



Pulse



Contours show where the newly formed current in the ionosphere maps to in the equatorial plane. Dotted lines are for positive currents in the ionosphere and solid lines are for negative currents.

First Response

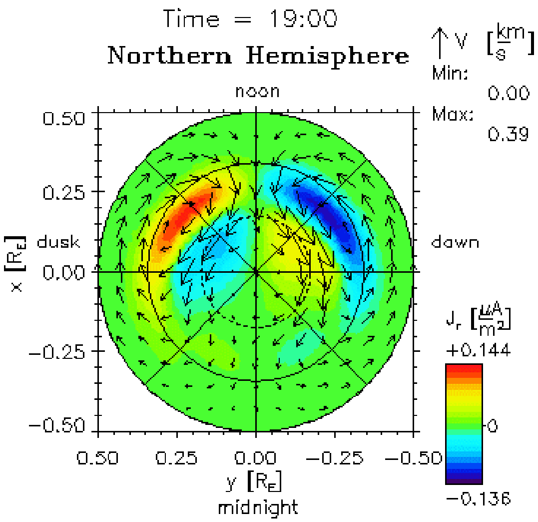
- The current pattern in the ionosphere for the first step case at 16 minutes is similar to the pattern in the ionosphere for the two steeper cases at 14 minutes.
- After 13 minutes, the current in the two steeper cases start to decrease. In the step case, the current for the first response reaches a maximum around 18-19 minutes. These times represent the approximate end of the density increase at the subsolar point of the magnetopause.
- In the magnetosphere, the newly-formed current in the ionosphere maps to similar regions. The first response in the ionosphere moves along a region inside but near the magnetopause. A second response is seen in the ionosphere starting at similar latitudes to the first response. This maps to a region in the magnetosphere that is initially similar to the first response.

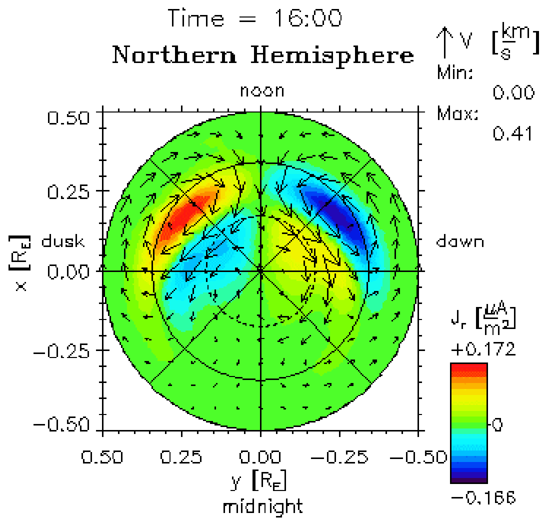
Second Response

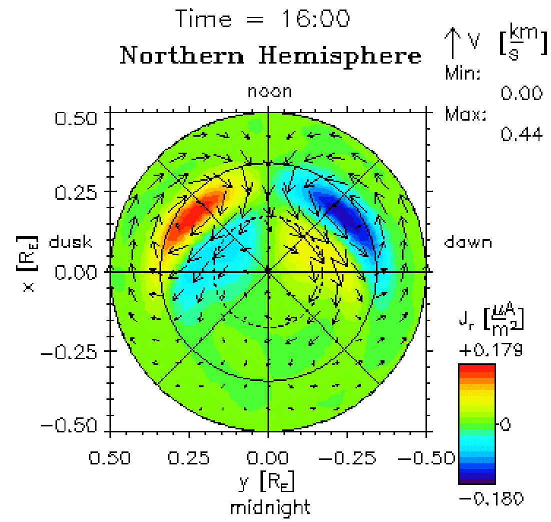
- The times shown are approximately 5 minutes after the midpoint of the density increase hits the magnetosphere. For the slower step increase, this time is 19 minutes. For the faster pulse, this time is 16 minutes.
- The second response in the ionosphere is qualitatively similar for both cases.
  - The increase in currents is seen at the same latitudes for both cases.
  - The velocity pattern is similar.
- The steeper cases have a slightly larger increase in the ionosphere but it is only about a 20-25% difference.
- In the magnetosphere, the cases look very similar. The mapping of the ionospheric currents to the equatorial plane for the second response stays inside the magnetosphere. This is different from the first response.
- The velocity patterns on the dayside inner magnetosphere region look very similar for all three cases.

Plots of the Ionosphere for the Second Response

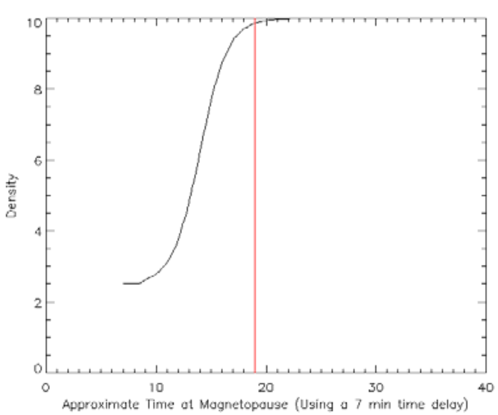
- Slow Step Increase
- Fast Step Increase
- Pulse

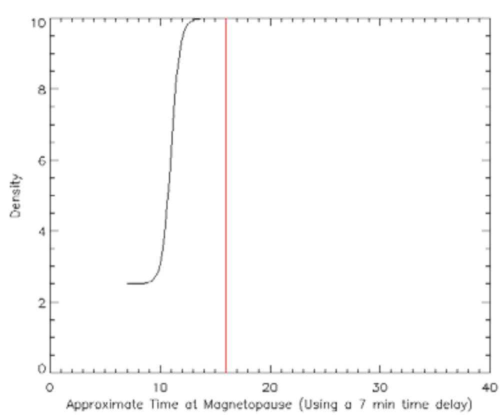


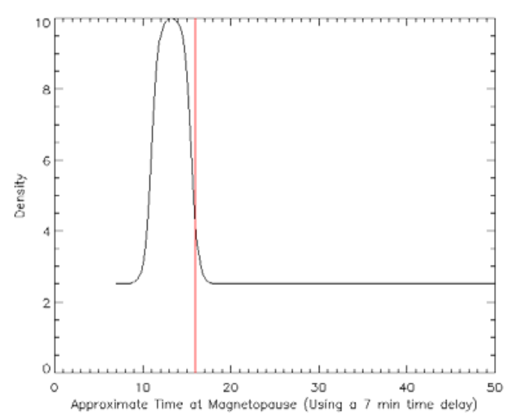




The current is the difference between t=19 and t=9 minutes. The velocity is the velocity at t=19 minutes.

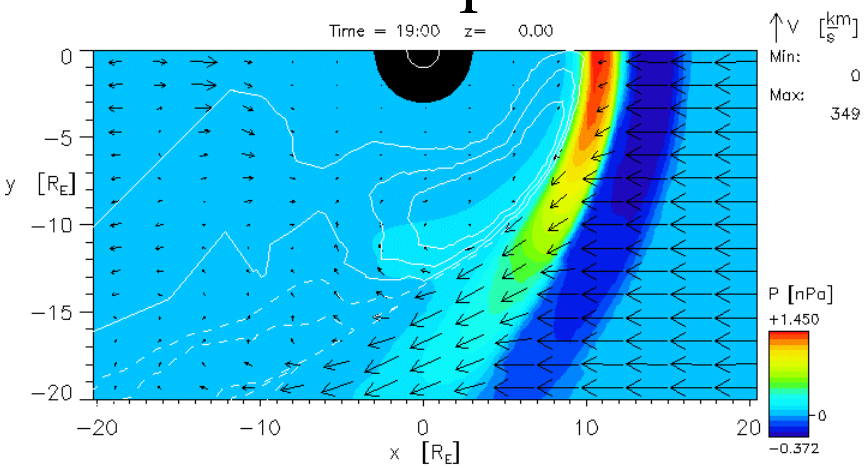




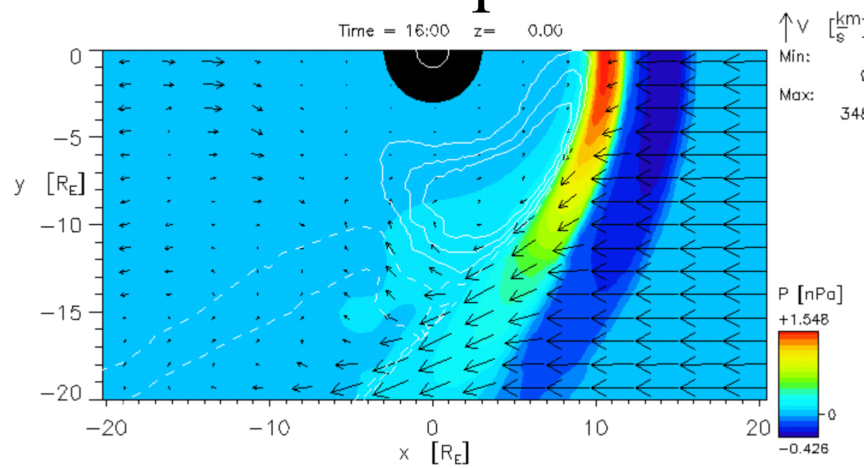


Velocity Plots in the Equatorial Plane

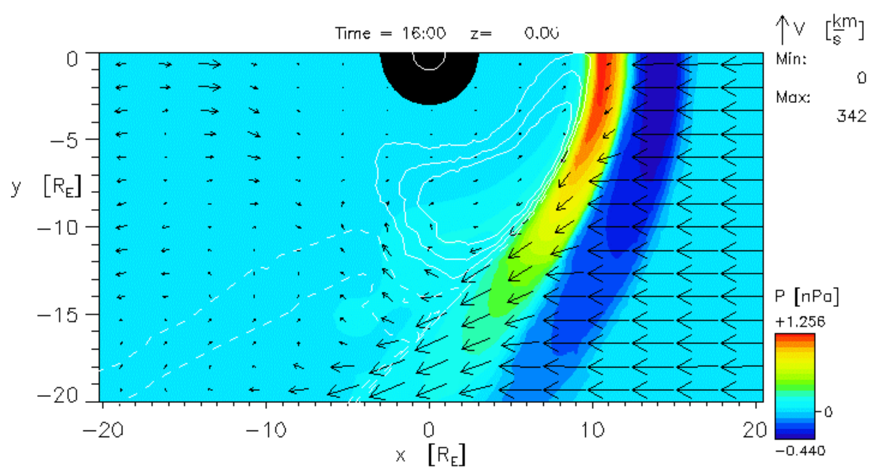
Slow Step



Fast Step

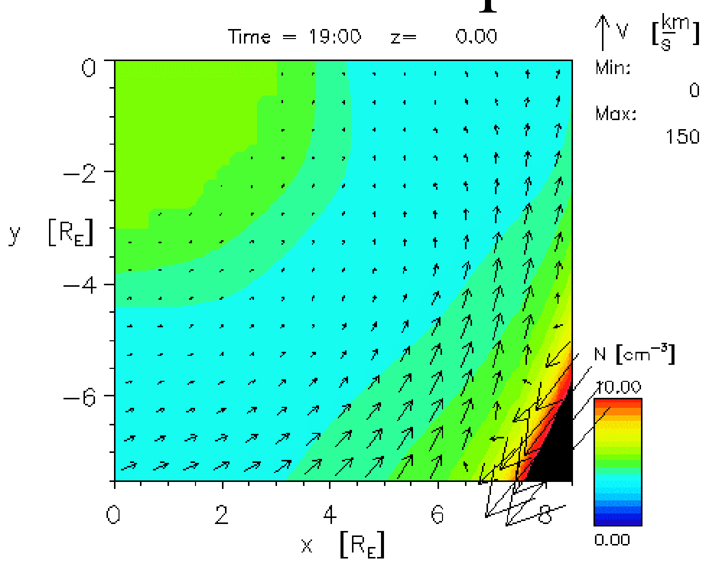


Pulse

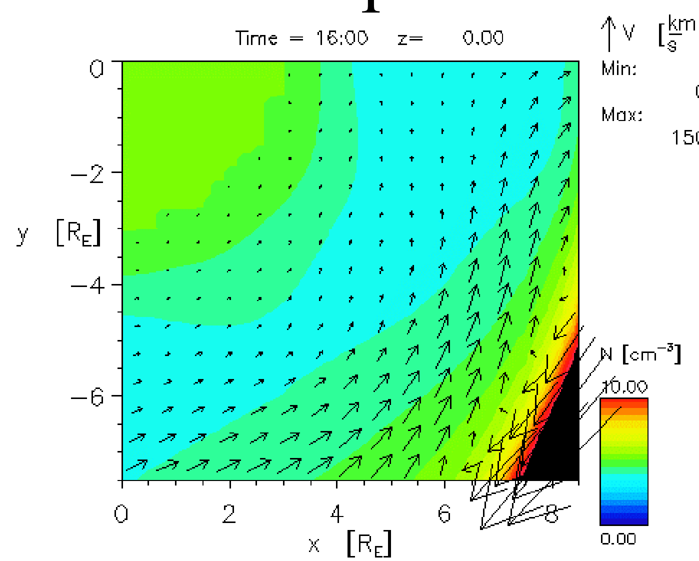


Velocity Plots in the Equatorial Plane

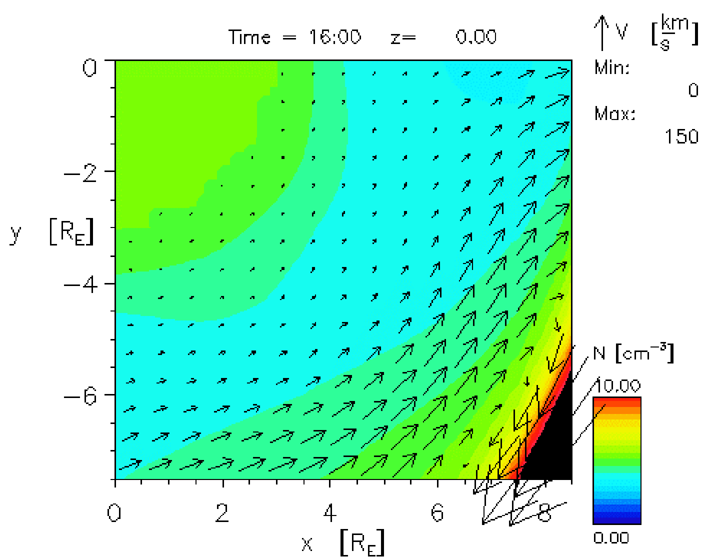
- Slow Step



- Fast Step

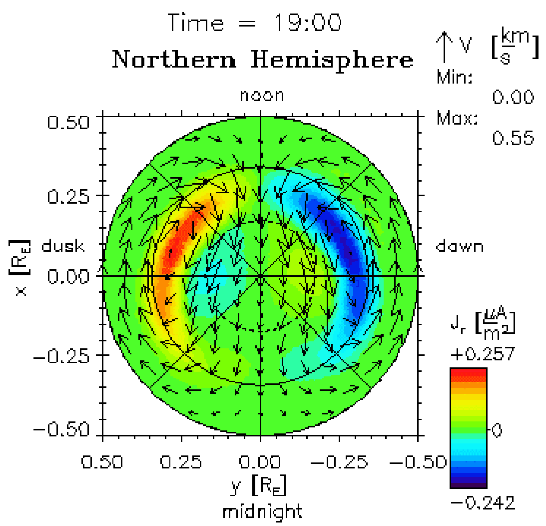


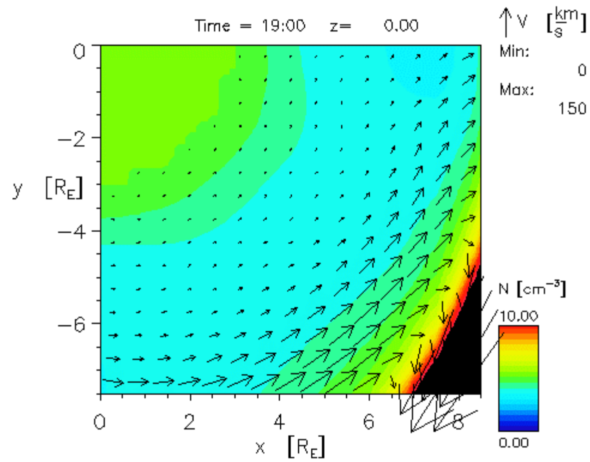
- Pulse

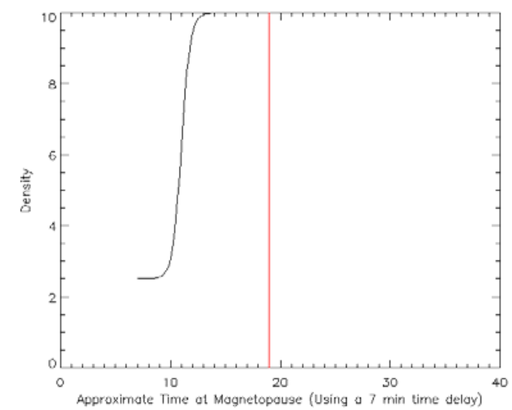


Configuration for Steeper Cases at *t* = 19 minutes

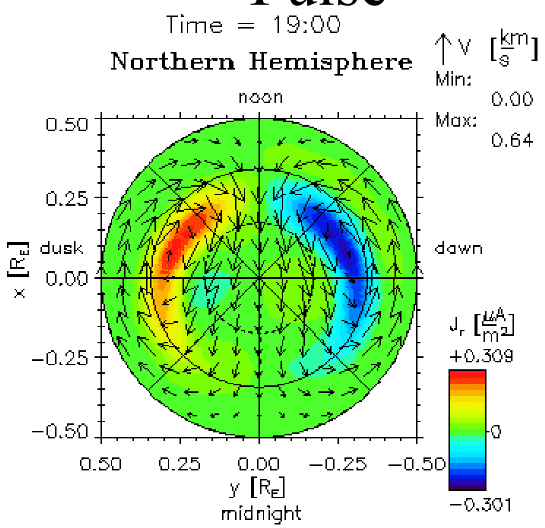
Fast Step Case

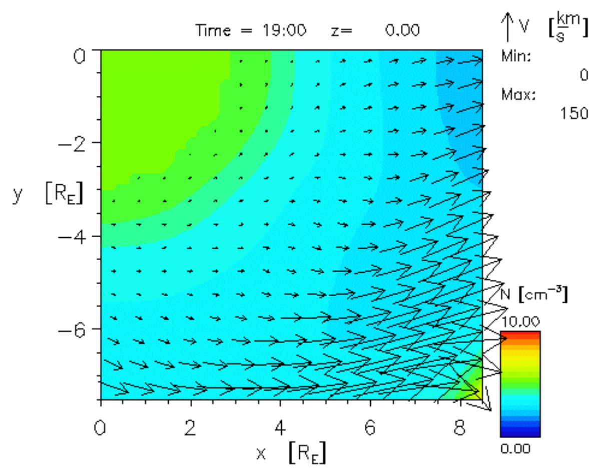


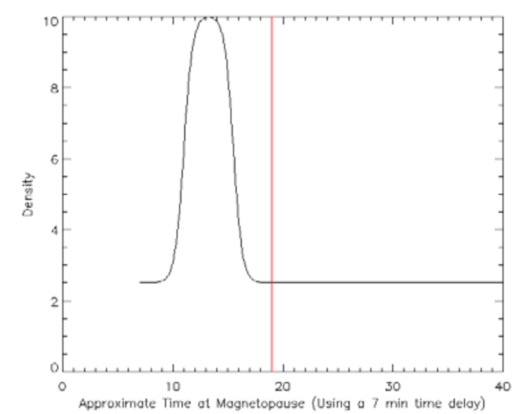




Pulse







Later Response in the Ionosphere

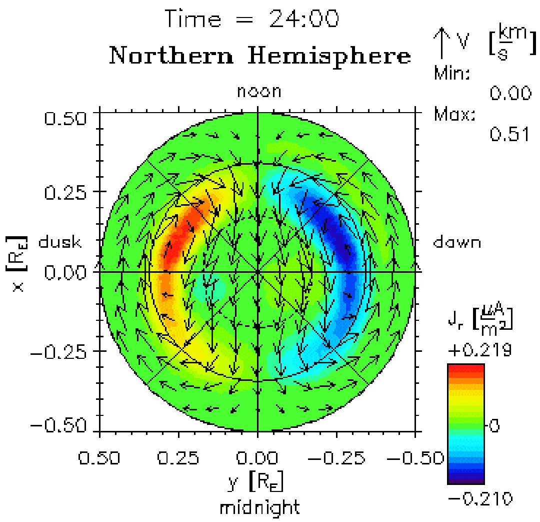
- For the pulse case, these responses occur after the entire pulse has passed the front edge of the magnetopause. For the step cases, the density increase has reached its maximum.
- For the slower step cases, the FACs in the ionosphere reach a maximum around t = 23 minutes. The magnitude of the currents slowly decay after this time. The pattern is roughly the same. For the steeper step cases, the maximum occurs around t = 19 minutes and is about 15% higher than for the slower step case.
- For the pulse case, the maximum occurs around t = 19 minutes and is about 38% higher than the the slower step case. There are multiple responses after the pulse moves past the magnetosphere. These signatures alternate polarity and decrease in magnitude. The fourth response occurs at higher latitudes than the rest of the responses.

Later responses in the Magnetosphere

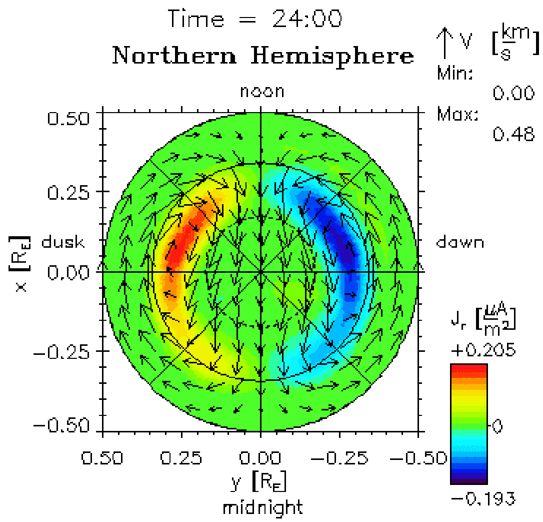
- The two step cases are very similar. Both have generated a large velocity shear near the magnetopause. This pattern is fairly stable for the rest of the simulation.
- For the pulse, the velocity pattern in not stable. There is a wake after the pulse has gone by. The magnitude of the velocity has also decreased.

Later Responses

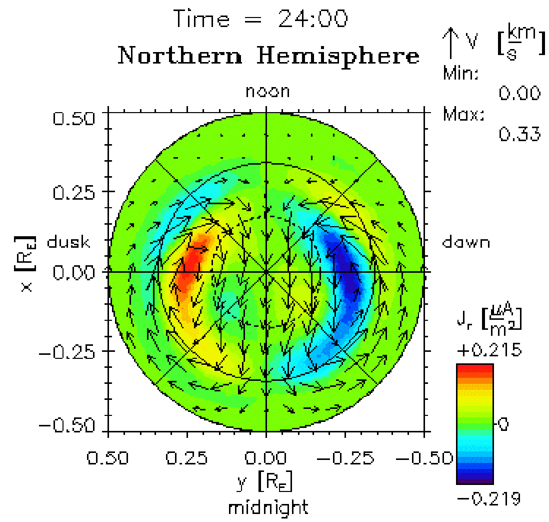
- Slow Step Increase



- Fast Step Increase



- Pulse

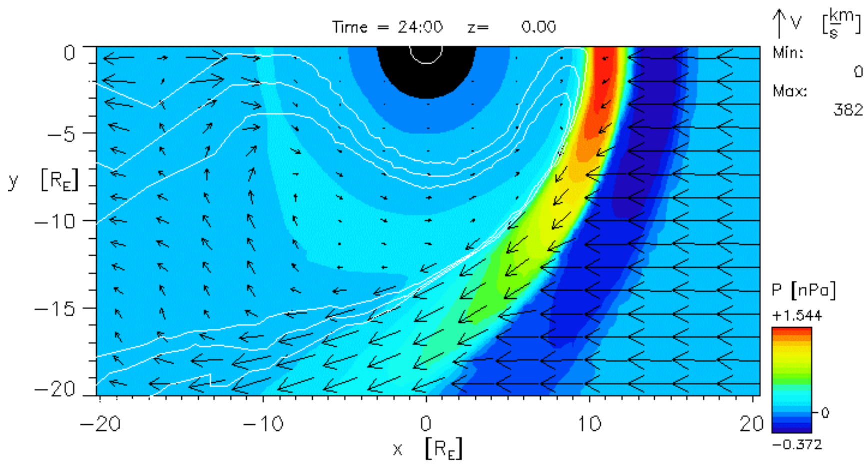


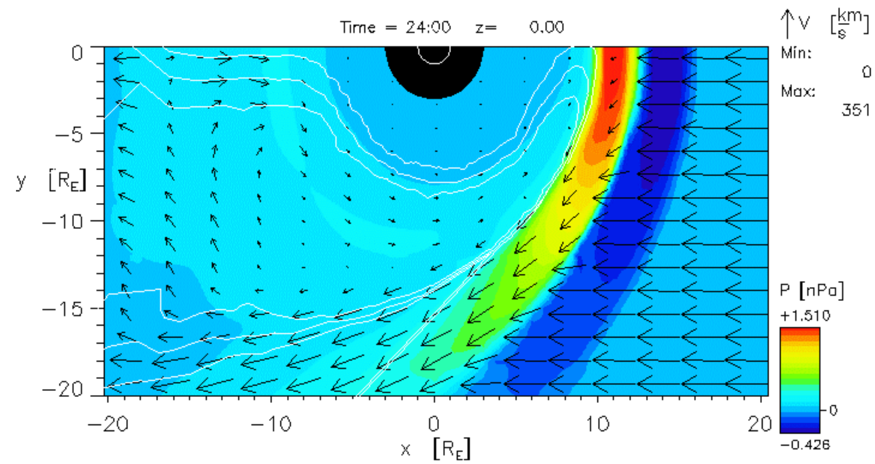
The current is a difference plot from t =9 minutes.

The vectors are velocity at the given time and not a difference plot.

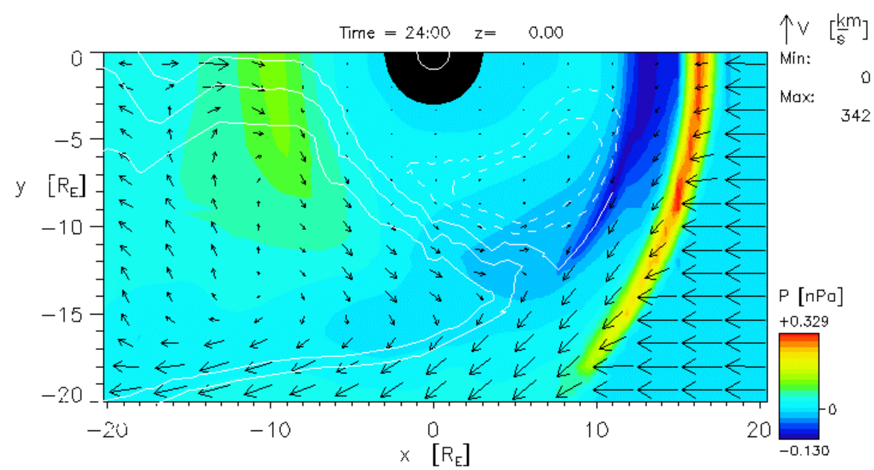
Velocity at t=24 minutes

- Slow Step
- Fast Step



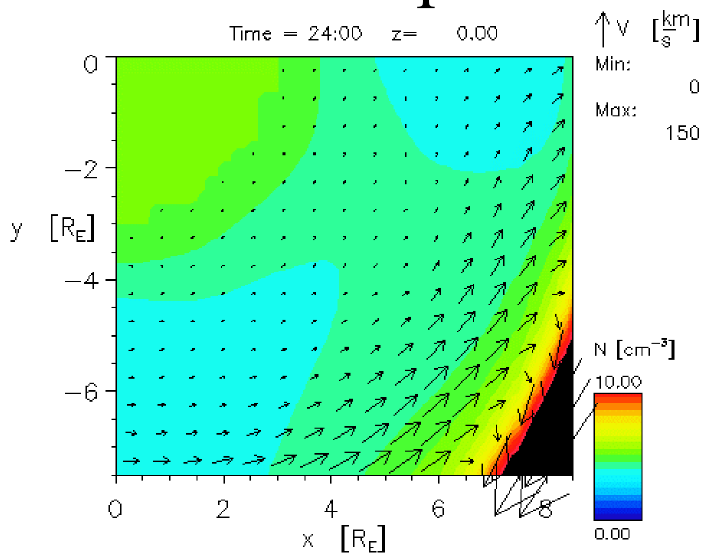


- Pulse

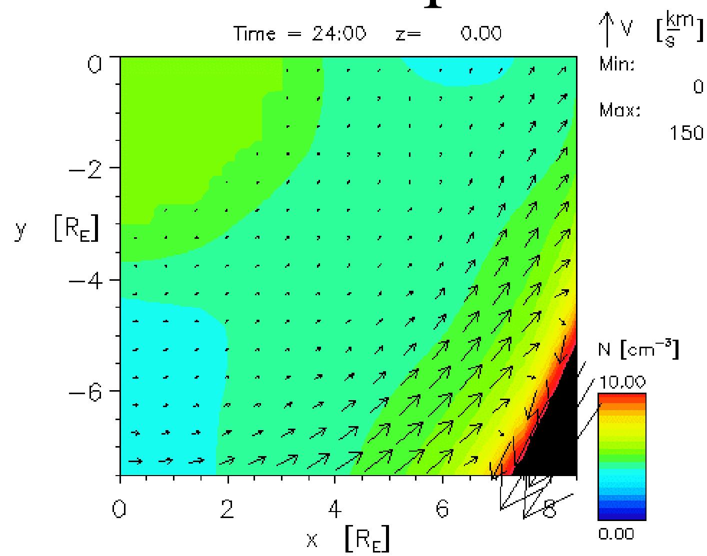


Velocity Plots at t=24 minutes

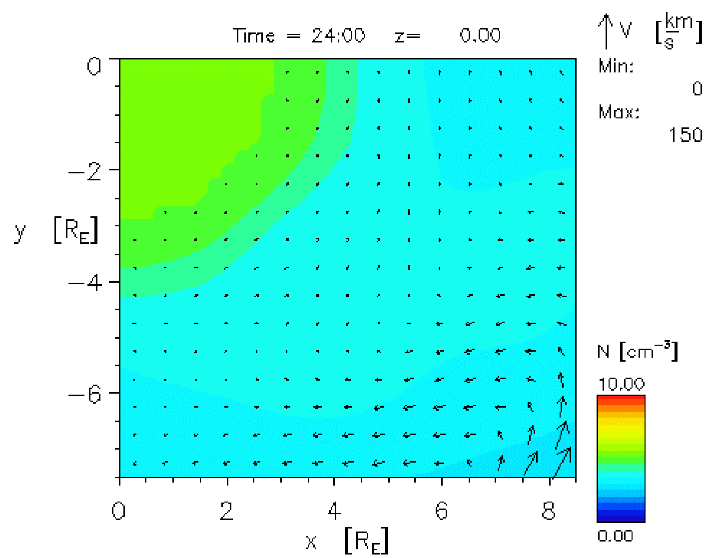
- Slow Step



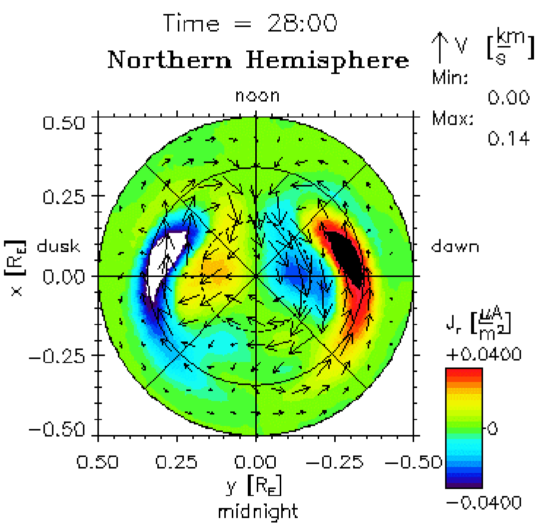
- Fast Step

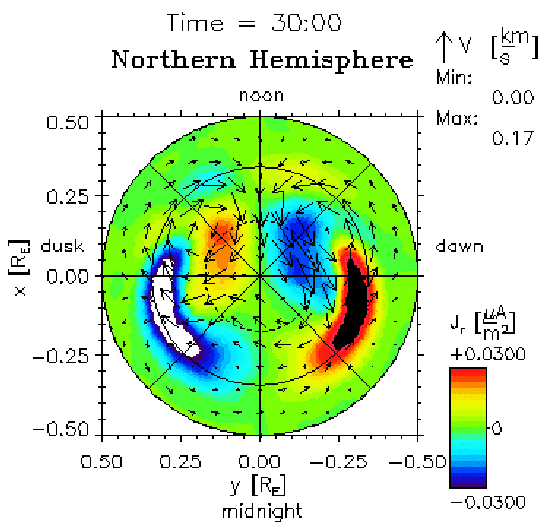


- Pulse



Later Response for the Pulse

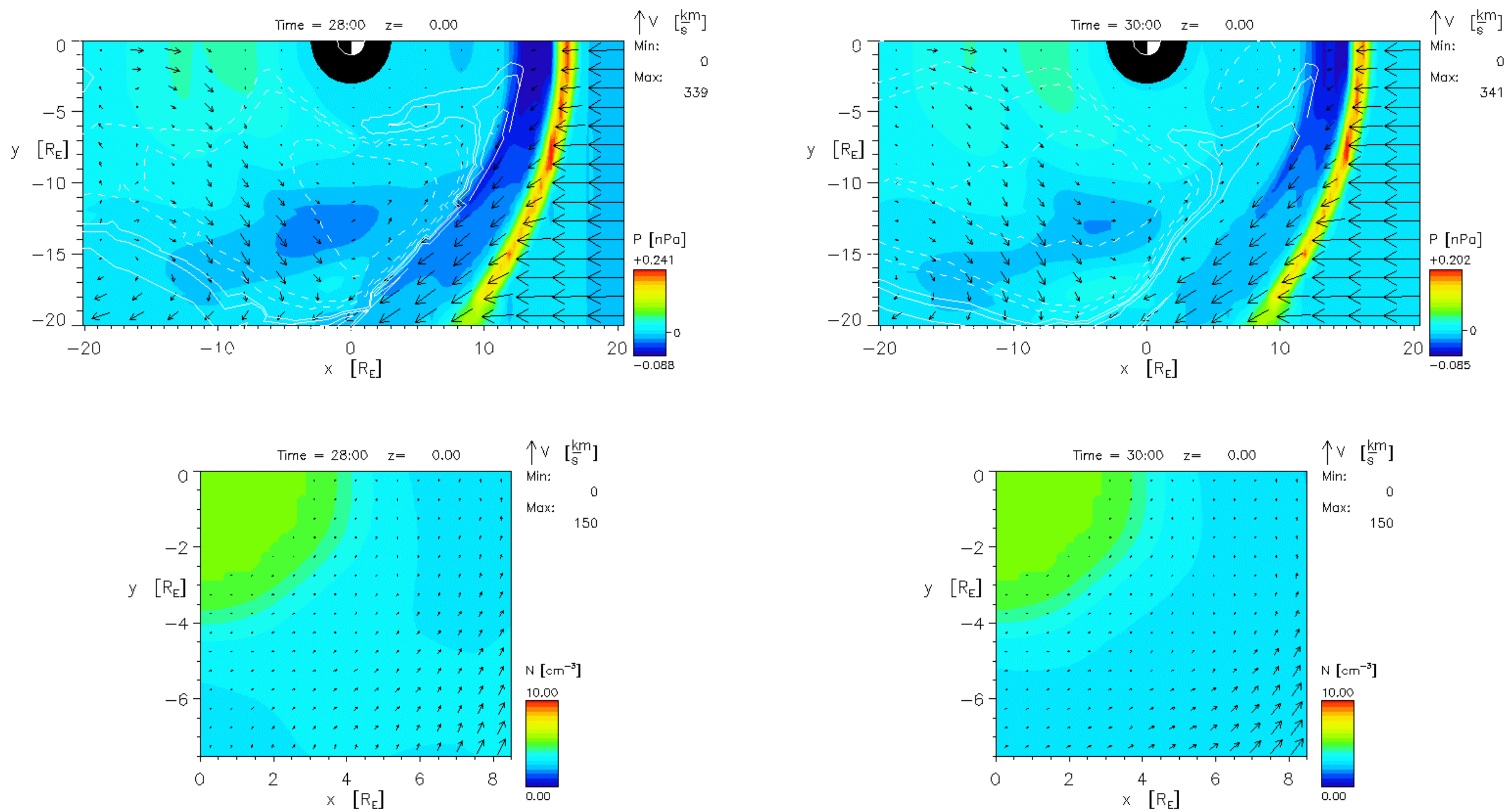




The current is a difference plot from t =9 minutes.

The vectors are velocity at the given time and not a difference plot.

Velocity for the Pulse Case



Responses for the Pulse Case

Response Polarity on Dawn side	Approximate Start Time	Maximum Current ($\mu A/m^2$) (Time)
1 Out of Ionosphere	10 minutes	0.116 (13 min)
2 Into Ionosphere	13-14 minutes	0.288 (19 min)
3 Out of Ionosphere	20 minutes	0.075 (25 min)
4 Into Ionosphere	27-28 minutes	0.032 (32 min)
5 Out of Ionosphere	28-29 minutes	0.0205 (37 min)

Location of FACs

- The location of the field-aligned currents (FACs) in the magnetosphere are similar in all three cases.
- For the first response, the FACs is inside but near the magnetopause and moves along the magnetopause as the density increase moves tailward. The location is near pressure perturbations along the magnetopause. This suggest a mechanism similar to Kivelson and Southwood [1991]. This response is significantly larger for the steeper cases.
- For the second response, the FACs are initially close the the magnetopause on the dayside and are located farther inside the magnetosphere at later times. This response is very similar for all three cases. The magnitude is only slightly larger for the steeper cases. This response is consistent with fast mode waves mode converting into Alfvén waves.

Conclusions

- The steepness of the density increase changes the magnitude of the first response. The initial change in current density in the ionosphere is 5-6 times larger for the steeper cases.
- The difference in magnitude between the three cases for the second response is not as large. The velocity patterns in the ionosphere and magnetosphere are similar for all three cases.
- In the steeper cases, the first response has a shorter duration. As the pulses passes, there are multiple responses that are not seen in the two step cases. In the magnetosphere, there is a wake behind the pulse and the velocity decreases while for the step increases the velocity pattern stabilizes into a velocity shear near the magnetopause.

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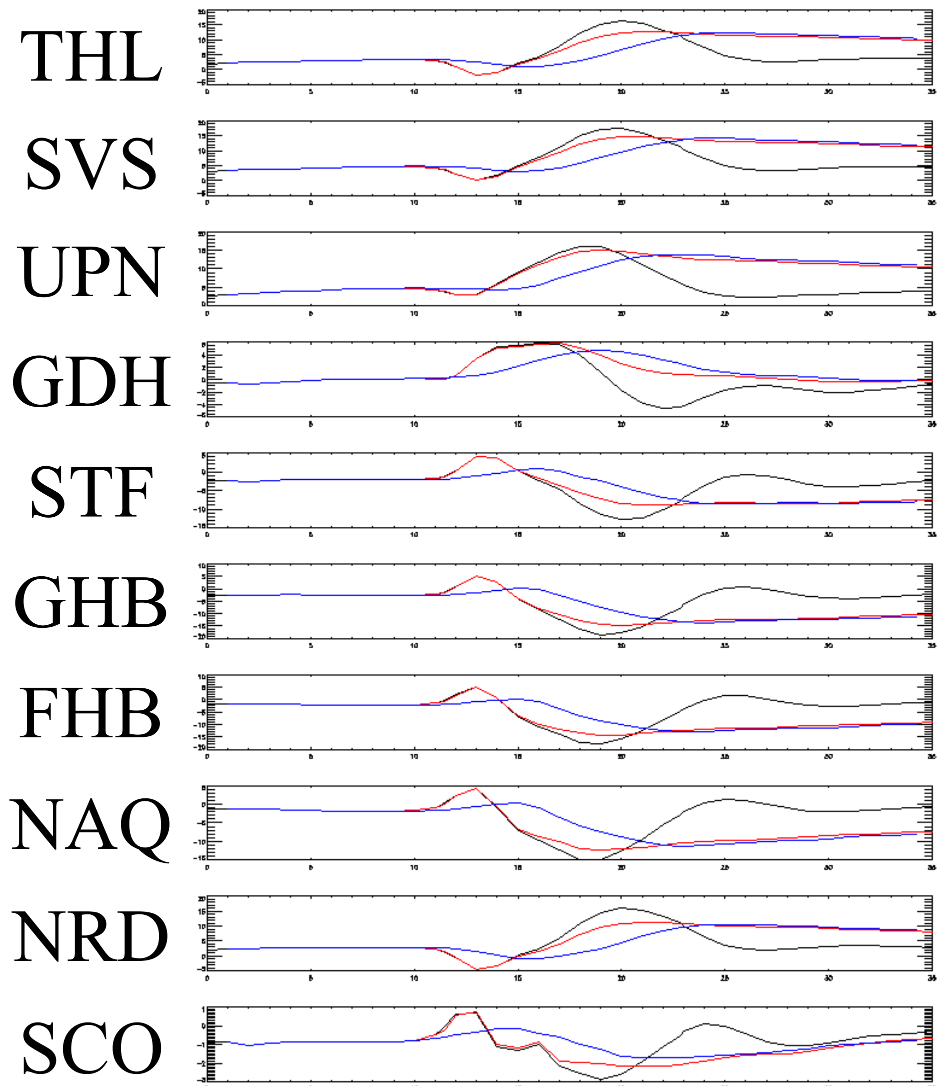
Magnetic Field Configuration at Ground
H Component



Blue: Slow Step

Red:Fast Step

Black: Pulse